REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
04/03/2001

2. REPORT TYPE
CONFERENCE PROCEEDINGS

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
BATHYMETRY AND BOTTOM ELECTRICAL PROPERTIES FROM AN AIRBORNE ELECTROMAGNETIC SURVEY AT KINGS BAY GEORGIA

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62315N

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
Will Avera and Ed Mozley

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Marine Geoscience Division
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL/PP/7440--00-1014

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Ballston #1
800 N. Quincy St.
Washington, DC 22217-5660

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution is unlimited.

20010816 033

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The Naval Research Laboratory deployed an advanced airborne electromagnetic (AEM) hydrographic system over the Kings Bay entrance channel to chart water depths and map variations in sea floor sediments. The survey consisted of three helicopter flights and resulted in the acquisition of high quality data that had the same areal coverage as two high density acoustic surveys. In addition, water temperature and conductivity measurements were acquired over the tidal cycle and along the surveyed channel. These data sets provided the ideal information to evaluate the capabilities of the AEM technology.

The interpretation of the AEM survey indicated that the inferred water conductivities agreed with in-situ measurements to an accuracy of 0.1 Siemens/meter. The average water depths provided by the AEM system along the 5300 foot survey lines deviated from the acoustic data by less than two feet. Seafloor conductivities were spatially coherent and provided realistic formation factors ranging from 3.2-9.5 that should correspond to variations in bottom material ranging from a clean consolidated sand to a poorly consolidated clay or silt.

15. SUBJECT TERMS
airborne electromagnetic hydrograhpic

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified		10	Will Avera

19b. TELEPHONE NUMBER *(Include area code)*
228-688-4778

Bathymetry And Bottom Electrical Properties From An Airborne Electromagnetic Survey At Kings Bay Georgia

Will Avera
Naval Research Laboratory
Stennis Space Center, MS USA

And

Ed Mozley
Space and Naval Warfare Systems Command
San Diego, CA USA

ABSTRACT

The Naval Research Laboratory (NRL) deployed an advanced airborne electromagnetic (AEM) hydrographic system over the Kings Bay entrance channel to chart water depths and map variations in sea floor sediments. The survey consisted of three helicopter flights and resulted in the acquisition of high quality data that had the same areal coverage as two high density acoustic surveys. In addition, water temperature and conductivity measurements were acquired over the tidal cycle and along the surveyed channel. These data sets provided the ideal information to evaluate the capabilities of the AEM technology.

The interpretation of the AEM survey indicated that the inferred water conductivities agreed with in-situ measurements to an accuracy of 0.1 Siemens/meter. The average water depths provided by the AEM system along a 1.6 kilometer survey line deviated from the acoustic data by less than 0.6 meter (two feet). Seafloor conductivities were spatially coherent and provided realistic formation factors ranging from 3.2-9.5 that should correspond to variations in bottom material ranging from a clean consolidated sand to a poorly consolidated clay or silt.

INTRODUCTION

The Naval Research Laboratory (NRL) has worked with airborne electromagnetic (AEM) techniques to develop a rapid tool for measuring bathymetry and bottom properties in coastal or shoreline locations. The AEM bathymetry technique is based on the utilization of the physical phenomenon of electromagnetic induction in the sea and sea floor sediments. Induction occurs whenever a time varying electromagnetic field is generated in the presence of an electrical conductor. For the case of an electromagnetic transmitter deployed above water overlying a saturated sedimentary sequence, the time varying primary fields will induce eddy currents within the water column which will in turn diffuse through the water into the sediments at a rate defined by the electrical conductivity of the media. The secondary fields, generated by the diffusive eddy currents provide a frequency response that reflects both the depth and conductivity of the water as well as the conductivity of the sediments.

An AEM system provides an innovative means to measure shallow water depths and electrical properties from a helicopter at air speeds of approximately 85 knots. The technology

produces a "quick look" at the coastal hydrography and can be a useful reconnaissance tool for sediment properties up to the beach. A major advantage of this technology is that it is flexible enough to operate in shallow water areas ranging from the beach through water depths in excess of 30 meters.

The AEM technique was developed in Canada during the 1950's as a mineral prospecting tool. Over the intervening years the technology evolved into sophisticated multi-frequency systems capable of mapping sedimentary cover. Initially the interpretation of AEM data for bathymetry required a great deal of effort to correct the measurements for calibration and system drift errors. In older high Q systems, the depth of penetration through the water was limited by the absence of low frequency capabilities and the resolution was constrained by the availability of only a fixed number of analog high Q frequency windows (one to three). Also, older systems required a large number of analog circuit elements that resulted in complex poorly calibrated systems with very high drift rates. These system traits made conventional AEM systems difficult to use for bathymetry and introduced a high degree of uncertainty in the interpretation of the data. To alleviate these problems, NRL (NOARL at the time) developed a digitally controlled wide band AEM system using the latest solid-state components.

SYSTEM DESCRIPTION

The NRL AEM system consists of two main elements: a tow body and a signal processing module. The cylindrical tow body is 6.4 meters long and 0.55 meters in diameter and is fabricated from a filament wound Kevlar to provide a rigid support for the AEM transmitter and receiver coils. It is deployed beneath a helicopter by a 50 meter tether during data acquisition. The signal processing equipment is located in the helicopter and contains the control computers and recorders. The system uses a wide band transmitter with digital electronic components to reduce the sensitivity to non-linear thermal drifts. A special design effort resulted in the identification and fabrication of appropriate coil mounts to compensate for the thermal expansion from high operating currents of the transmitter coil. The design considerations were exceptionally successful and resulted in an overall system drift of less than 15 parts per million (ppm)/hour.

The tow body contains two primary operational units: the transmitter and the receiver. The wide band transmitter allows the generation of arbitrarily complex fields while maintaining the power efficiency of tuned systems. The main element of the transmitter unit is a MOSFET H-bridge circuit that controls the current flowing in the transmitting coil by adding or subtracting short energy pulses under digital control. At the peak primary moment of 1600 A-m^2, the circulating current reaches 40 amps while only drawing 1 amp from the main power supply. Auxiliary circuits in the transmitter module prevent failures that could interrupt the current flow in the H-bridge drive circuitry and thereby damage the MOSFET components.

The receiver consists of two counter wound coils and a two channel, low noise, high gain pre-amplifier. The signal coil is larger and mounted farthest from the transmitter coil and the bucking coil is smaller but mounted closer. This configuration effectively nulls the primary field out of the signal coil. Nulling the primary field is necessary to limit the dynamic range of the measured fields and permit accurate measurement of the much weaker secondary fields originating in the underlying conductive media. Both the secondary and the primary fields (for normalizing) are amplified and sent up the tether to the signal processor.

The signal processing module controls the transmitter, pre-processes the received data and provides various in-flight diagnostic functions. All of the processing functions are slaved to a master clock to provide very high accuracy phase information. A bit stream representing the desired wave form is continuously sent to the H-bridge transmitter in the tow body while the received signal is synchronously convolved with the frequency components of the transmitted wave form. The resulting inphase and quadrature responses are recorded on tape 30 times per second.

For the data presented in this paper, the systems controller was limited to three frequencies due to limitations of the signal processing module. After the Kings Bay test, a high-speed data logger was incorporated into the system to record the complete time series signal. The full time series record will permit extensive data post-processing to remove noise components and will expand the system's ability to operate at more than three frequencies. In addition, the modified system could easily be extended to operate in a pulse mode configuration with additional changes to the transmitter.

The system footprint (spatial response function) is a spatial smoothing of the ocean bottom and has a circular geometry. For features smaller than the footprint, the accuracy of the one-dimensional interpretation for water depth degrades significantly. Small bottom features within the footprint are spatially integrated into the depth determination. The radius of the footprint is approximately equal to the altitude of the towed body. To a lesser degree, the footprint size is also a function of water depth, frequency and conductivity.

KINGS BAY FIELD TEST

A field test of the AEM bathymetry concept was conducted at Kings Bay, Georgia in June 1990 around the harbor entrance. In addition, two acoustic hydrographic surveys over the Kings Bay ship channel were scheduled for nearly the same time period. This data provided excellent ground truth for evaluating the AEM bathymetric interpretation. Additional details about the field test are contained in reference 1.

Woods Hole Oceanographic Institution conducted a hydrographic survey in accordance with IHO standards over the harbor channel independent of the AEM test. The Woods Hole lines are oriented north-south across the Kings Bay channel and extend approximately one kilometer long inside the jetties and 1.6 kilometers long seaward of the jetties. Lines are spaced approximately 200 feet apart. In addition, the U.S. Army Corps of Engineers (COE) conducted a quarterly survey of the channel to search for areas of silting. The perpendicular lines that they surveyed were shorter than those provided by Woods Hole. These lines ranged from 150 meters to one kilometer in length, and line spacing varied from 7.5 meters to 30 meters.

In-situ water conductivity measurements were taken to evaluate the interpreted water conductivities provided by the AEM system. Measurements were acquired in the Kings Bay entrance channel on June 20-22 using a hand deployed conductivity temperature depth (CTD) measurement instrument. This provided a sufficient number of samples during a tidal cycle to permit a comparison between the CTD and the remotely measured AEM conductivities. Average conductivities indicate that the conductivity in the channel varied by about 0.1 Siemens/meter between high and low tide.

The AEM data were acquired in four flights lasting approximately four hours each. Most lines were flown with a tow body altitude of 23-32 meters. The data consist of approximately 57 north-south lines covering a 6.5 kilometer wide by 8 kilometer long region

around the harbor channel. In addition, data were acquired along the channel with a few east-west oriented tie lines. The primary lines were acquired with a north-south orientation because of the east-west orientation of the channel and the north-south heading of the acoustic survey lines. In addition, past experience indicated that AEM data acquired with a north magnetic heading provided a better signal to noise ratio. In order to allow time for the AEM tow body to stabilize before entering the area, the north-south lines were extended well beyond the acoustic survey area.

Navigation for the AEM data was provided by a Del Norte microwave transponder system with three remote sites. The Del Norte Distance Measurement unit (DMU) was programmed with the survey plan and was used to guide the helicopter pilots between waypoints via a small cockpit display. The transponder system has a best-case accuracy of two meters, but the realized accuracy in this survey is more likely close to five meter. The master unit was mounted in the helicopter with the antenna extended beneath the fuselage. The aircraft position was recorded on a laptop computer once per second.

DATA PROCESSING

The main components of the processing flow for the inversion of the AEM data are as follows: remove offsets and drift, invert for parameters (depth, conductivity, etc.), apply time correction (if necessary), merge navigation information and plot results. To reduce processing time and data storage requirements, the data were time averaged over 5 points resulting in a spatial sampling window of approximately 7.5 meters.

The most important element of the AEM interpretation is associated with determination of an accurate calibration for the system. This step in the processing procedure is required only once after any hardware change has been introduced into the system. The calibration defines the degree from which the ratio between the amplitude and phase of the signal and bucking channels vary from unity. The calibration function was determined by comparing AEM field data with acoustic water depths and in-situ water conductivity measurements at several selected points. The seafloor conductivity was allowed to vary, since ground truth information was not available for this parameter. The calibration procedure minimizes the difference between the required system functions at two locations with known water depths and conductivities provided by CTD and acoustic measurements. The algorithm is based on the assumptions that the calibration function is constant over time and that bottom conductivity doesn't change significantly within a small region.

In addition to the system calibration, the data must be corrected for temporal drifts associated with temperature changes in the system. The temporal drifts in the AEM system are determined by periodic high altitude checks. An offset or baseline value for each frequency is determined by rising to an altitude on the order of 600 meters during each flight. At this altitude, the ocean has no effect on the AEM system. The high altitude drift measurements are applied to the data then the system calibration is applied to correct the recorded data for system dependent factors.

The resulting corrected data are inverted for the tow body altitude, water depth, water conductivity and bottom conductivity by an iterative least squares algorithm. The inversion routine uses a 1-D layered forward model computation for the transmitter and receiver in air above a conductive water layer overlying a conductive half-space. Inphase and quadrature values are computed for each frequency and compared with the observed data for each point.

An iterative least-squares optimization is used to determine the best model parameters for each point. Each measurement point is solved independently with the previous solutions for depth and altitude used as starting values. The program attempted to close to a solution up to five times with various search parameters. A solution is accepted only if successive iterations agree to three significant digits. The inversion output consists of the solution parameters, and an error value for each point. The error value is the sum of the squares of the misfit between the measured data and the forward model computation with the final model parameters. A misfit of less than 3 ppm indicated a good fit.

The inverted water depth is compensated for known tidal variations (for comparison with conventional hydrographic data) and merged with the navigation information to determine the bathymetry at each point. To smooth the final data, a three point median filter is convolved across the parameters. The median filter determines whether the magnitude of a middle point is between the magnitudes at the end points. If it is not, the average magnitude of the two points with the nearest or most similar magnitudes is substituted for the midpoint. This filter does not severely flatten real peaks and dips in the data, but it does effectively remove extreme values

To establish an accurate means to compare the AEM results with the ground truth, the acoustic data were interpolated onto a uniform grid and then linearly interpolated onto the AEM flight tracks. This procedure minimized apparent depth errors caused by positioning differences in the two data sets. Since the acoustic lines were acquired at a consistently higher density than the AEM lines, they could be interpolated onto a fine 7.5 meter grid with a high degree of accuracy. A linear interpolation scheme was used to estimate acoustic depths within the grid cells to match sample locations along each of the AEM profile tracks. The results of this processing step provided an accurate means to compare the acoustic and AEM water depths, which were measured on different traces, along common profiles.

DATA EVALUATION AND SURVEY RESULTS

The first comparison between the AEM and acoustic water depths is made with the COE data (acquired in early July 1990). These data are also used to calculate the system function for the AEM. A comparison, between the water depths derived from the calibrated AEM system and the COE acoustic survey, is presented along a north-south profile in figure 1 in units of feet to be consistent with the COE survey results. The ordinate of the graph is in feet below mean low water and abscissa defines the distance along the profile in thousands of feet (with north to the right). The dashed trace on this graph indicates the AEM derived water depth and the solid trace represents the acoustic water depth. The difference (residual) between the two depth estimates is plotted at the top with dots. The residual plot shows that the depths agree very well except over the steep north side of the channel where the AEM data has shallower depths. The difference could be due to registration errors (differences in the relative location of the measurements) and to depth averaging caused by the AEM footprint. The average of the residual over the one kilometer (3500 feet) profile is 0.5 meters (1.7 feet) with a standard deviation of 0.46 meters (1.5 feet).

The Woods Hole acoustic survey has a more extensive coverage than the COE data and will be used to compare the mapped bathymetry with the AEM data. Since the AEM line spacing is much larger than the acoustic survey line spacing, the acoustic water depths are interpolated onto a uniform 15 meter (50 feet) square grid cell for comparison. Both the AEM and acoustic water depths are presented in figure 2 as grayscale charts with a five foot precision.

The top chart in this figure represents the residual or the difference between the AEM and acoustic depths and has been contoured with a two foot precision. It is important to note that a major portion of the residual chart is covered by the grayscale values within two feet of the zero grayscale. Much of the difference (residual) in the two surveys could be caused by spatial aliasing from the large AEM line spacing. The dark areas (indicating large deviations on the residual chart) are found to be located between AEM flight lines. The distribution of the residuals for the north-south lines used in figure 2 is shown in figure 3. The RMS deviation of the data is 0.576 meters (1.89 feet) with a mean of 0.04 meters (0.15 feet) and standard deviation of 0.53 meters (1.73 feet).

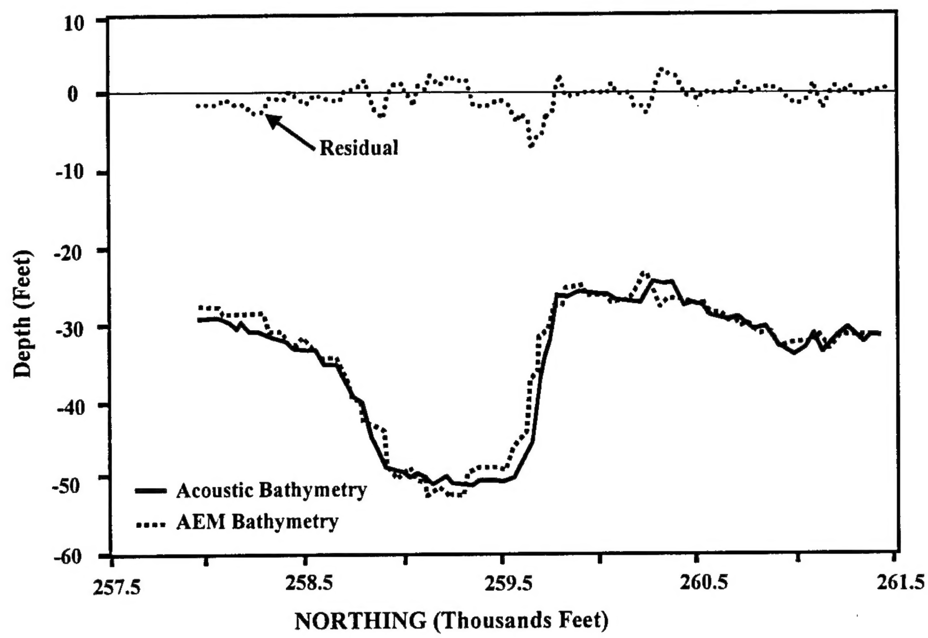

Figure 1 A comparison between AEM derived water depth and U.S. Army Corps of Engineers (COE) acoustic hydrographic survey for a north-south profile. Units are in feet to be consistent with the COE survey results.

In addition to bathymetry, water and seafloor conductivity estimates are produced from the interpretation of the AEM data. Several AEM survey lines were flown east-west over the length of the channel on June 24th and 25th. While these measurements were not obtained at the same time as the CTD measurements, it is possible to compare them in relationship to the tidal cycle. Figure 4 shows the water conductivity from the AEM interpretation along two lines compared with the measured CTD water conductivity for the same time period in the tidal cycle. The upper trace represents the AEM interpreted water conductivity flown at low tide compared with the CTD measurements (squares) obtained one half hour before low tide. The lower trace represents the AEM conductivity for a line flown two hours after high tide and is compared with CTD measurements (triangles) also obtained two hours after high tide. These data show that the AEM measurements are highly correlated with an average shift in conductivity of more than 0.1 S/m and are consistent with the measured trend of decreasing values from west to east on both

portions of the tidal cycle. The root mean square value of the difference between the AEM and CTD measurements is 0.03 Siemens/meter.

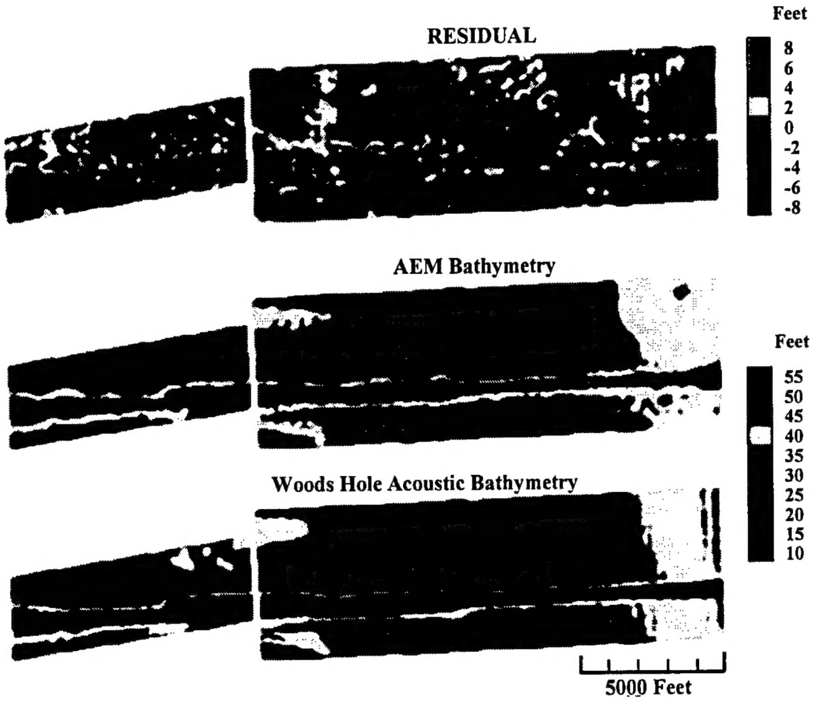

Figure 2 Maps of data covering the Kings Bay ship channel are shown for the acoustic and AEM data sources along with the residual (difference) between these surveys.

Figure 5 presents a chart of the entire AEM bathymetry data. The chart was constructed by interpolating all AEM water depth values onto a 15 meter (50 feet) square grid. The resulting contours are very similar to comparable features on standard National Oceanic and Atmospheric Administration (NOAA) hydrographic charts for the same area. The center of the survey area is dominated by a well developed river delta that is bisected by the dredged ship channel. Comparison of the AEM chart with the NOAA chart indicates that the mushroom shaped delta structure appears to have migrated to the east and south over the intervening time.

The AEM technique also produces an average seafloor conductivity measure in addition to the water parameters. Seafloor conductivity measurements can be related to geotechnical properties such as porosity, sediment type, and density through the empirical power law known as Archie's Law. In this relationship, the formation factor (seafloor resistivity normalized by the water resistivity) is related to the porosity raised to a negative power.

The AEM bottom conductivities are interpolated onto the same coverage grid and plotted in figure 6. The shallow near shore region is characterized by formation factors ranging from 7.1 to 9.5 (from 0.6 to 0.8 Siemens/meter), which correspond to a well consolidated sand with a 30 to 40 percent porosity. In the deeper water on the east side of the survey area, the conductivities are consistently greater than 1.3 Siemens/meter with peak values as high as 1.8 Siemens/meter, which translate into formation factors ranging from 3.2 to 4.4. This range of formation factors indicates that these areas are probably composed of a poorly consolidated silt or clay. Over the river delta, the pattern of conductivities is quite complex with formation factors ranging from 4.4 to 7.1. These data provide a high density database to investigate

depositional patterns; however, some type of in-situ measurements should be acquired to verify the proposed interpretation.

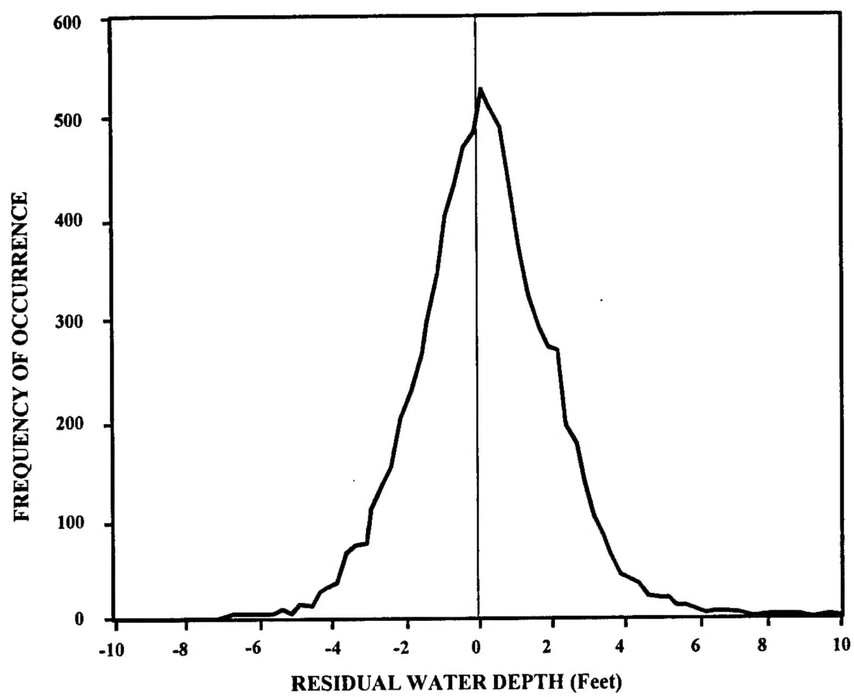

Figure 3 Histogram of the residual (AEM minus acoustic) water depth distribution for AEM north-south lines used to generate figure 2.

CONCLUSIONS

The overall data suite indicates that the average root mean square error (AEM depths minus acoustic depths) over the data set is approximately 2 feet and that the water conductivities are accurate to at least 0.1 Siemens/meter. In addition, seafloor electrical properties were measured that are spatially coherent and provided realistic formation factors ranging from 3.2-9.5 which should correspond to variations in bottom material ranging from a clean consolidated sand to a poorly consolidated clay or silt. These data were acquired with a Navy RH-53 helicopter that had very good vertical control. The good vertical stability of this helicopter is considered a significant factor in the acquisition of very high quality data during this survey.

ACKNOWLEDGMENTS

This paper is funded by the Office of Naval Research under Program Element 0602315N managed by Roy Wilkens and by the Naval Research Laboratory under Program Element 0602345N. The original airborne electromagnetic hydrographic survey conducted at Kings Bay, Georgia and the data processing associated with this project were funded by CNO (OP-096) through program element 0603704N under the management of Kenneth Ferer. Motivation to conduct the survey and ground support to acquire water conductivity data was provided by CAPT J.A. Nuernberger Commanding Officer of the Naval Submarine

Base, Kings Bay, GA. The acoustic data and navigation support were supplied by David Aubrey, Woods Hole Oceanographic Institution (WHOI). Mr. Brian Blake U.S. Army Corps of Engineers, Jacksonville District provided navigation support for the AEM survey and supplied acoustic data for AEM system calibration and evaluation.

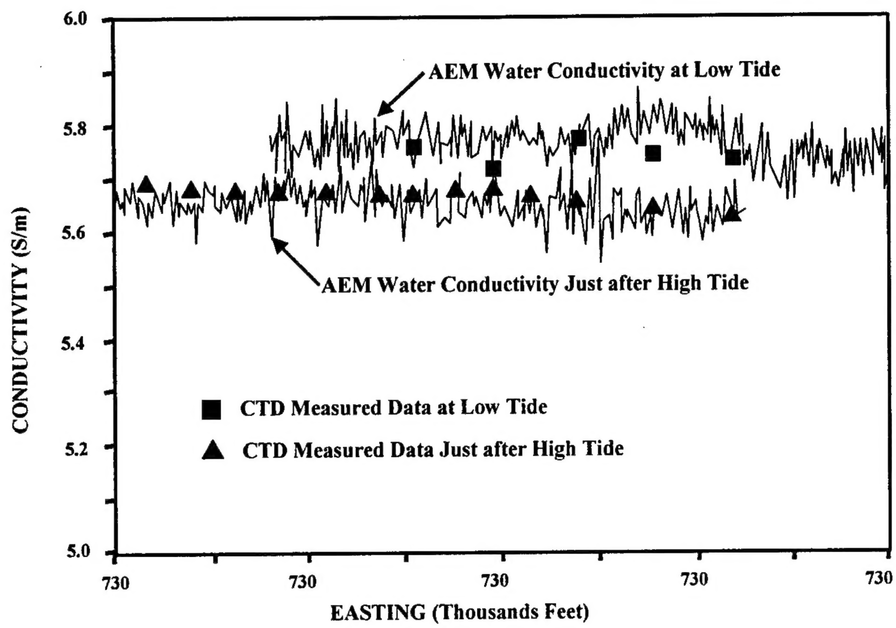

Figure 4 AEM derived water conductivity is compared with measured data from a CTD instrument.

REFERENCES

1. Edward C. Mozley, Timothy Kooney, David Byman, and Daniel Fraley, 'Kings Bay Airborne Electromagnetic Survey,' Naval Oceanographic and Atmospheric Research Laboratory, Code 352 (now Naval Research Laboratory, Code 7440), Report ID 019:352:91, April 16, 1991.

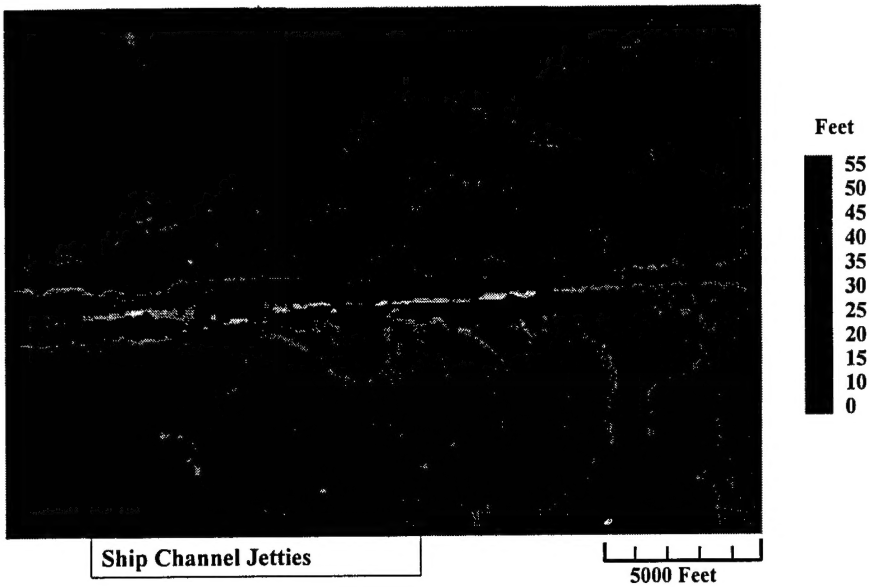

Figure 5 Regional bathymetric chart produced from AEM data covering the Kings Bay ship channel.

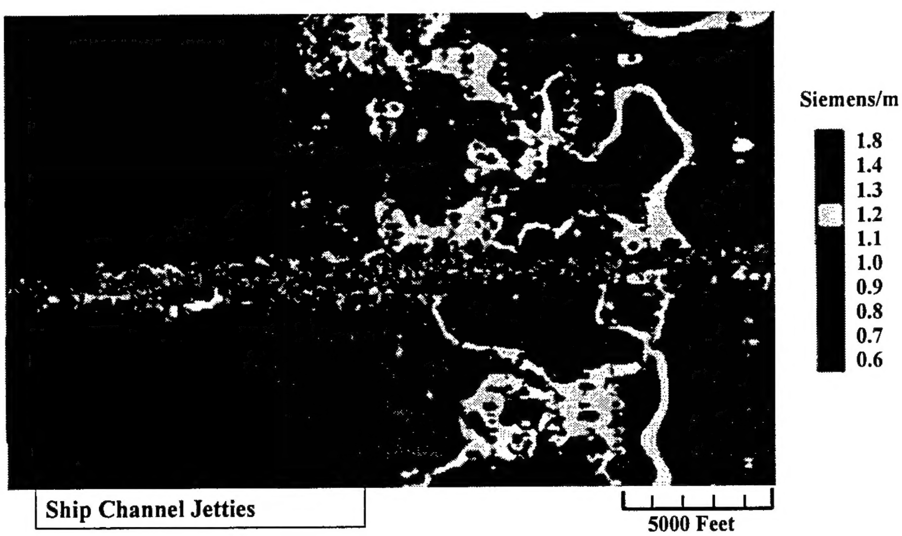

Figure 6 The regional bottom conductivity map derived from the AEM data.